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Abstract

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Keywords

Gippsland Lakes, coastal barriers, chronology, thermoluminescence dating, Late Pleistocene, tsunami

Disciplines

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LATE PLEISTOCENE MARINE CHRONOLOGY OF THE GIPPSLAND LAKES REGION, AUSTRALIA

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Abstract: Thermoluminescence dating is used to define the chronology of the coastal barriers of the Gippsland Lakes region, Australia. The area evidences a long history of marine deposition extending back to the Middle Pleistocene. However, the majority of Pleistocene barriers have formed since the Last Interglacial during two phases at 59 to 72 ka and 40 to 48 ka corresponding to interstadials. A third phase, with dates around the Last Glacial, appears to represent rapid shoreward movement of Late Pleistocene sediment from the shelf during the Holocene. Barriers have developed in an en echelon fashion seaward as the region has been uplifted tectonically. Some Late Pleistocene marine deposits reach elevations of 40 m above present sea level. These elevations imply rates of tectonic uplift exceeding 80 mm per thousand years, rates that may have increased toward the present. Deposits are preserved as isolated remnants because of subsequent fluvial and marine erosion. Both erosion and rebuilding may have occurred under the influence of tsunami originating from the south Tasman Sea. The unique distribution and preservation of recurrent interstadial barriers in the Gippsland Lakes region reflect rapid uplift, abundant sand supplies, and the proximity of this coast to sources for tsunami. [Key words: Gippsland Lakes, coastal barriers, chronology, thermoluminescence dating, Late Pleistocene, tsunami.]

INTRODUCTION

The use in Australia of modern dating techniques, such as uranium series disequilibrium as applied to ferruginous concretions, amino acid racemization, electron spin resonance, and thermoluminescence (TL), has permitted the dating of coastal sediments in those environments not only where carbon is lacking, but also where deposition of sands occurred more than 40,000 years ago, the upper limit for conventional ^{14}C dating (Belperio et al., 1984; Murray-Wallace and Belperio, 1991; Huntley et al., 1993; Bryant et al., 1994, 1997). Thermoluminescence analysis has been successful in dating many coastal deposits along the New South Wales coastline (Young et al., 1993; Bryant et al., 1994, 1997). Here, barrier deposits have been found not only from the oxygen isotope substage 5e, the peak of the Last Interglacial, but also from substage 5a. Fragments of earlier interglacial marine barriers also have been identified. More significantly, numerous marine deposits have been found above present sea level dating to less than 80 ka, which is the perceived lower limit of the Last Interglacial high sea level stillstand (Ku et al., 1990).

Pleistocene barriers were first studied in detail in Australia in the Gippsland Lakes region of Victoria (Fig. 1). Here, Bird (1961, 1978) identified an "Inner"

Fig. 1. Location map of place names and site locations of TL dates listed in Table 1. Maps A and B show the Gippsland Lakes and Corner Inlet regions, respectively, in more detail.

barrier of Late Pleistocene age and an "Outer" barrier of Holocene age. This classification was extended to New South Wales by Langford-Smith and Thom (1969), where the Inner barrier was interpreted as a Last Interglacial substage 5e feature. Bird never made any such claim. Rather, he viewed the Inner barrier of the Gippsland Lakes as a Late Pleistocene composite feature. Ward (1977) went further and postulated, on the basis of soil development, that much of the Inner barrier and landward coastal features were 42.5 ka old. The purpose of this paper is to assess, using mainly TL dating, the chronology of the Gippsland Lakes barriers between Lake Tyers in the east and Wilsons Promontory in the west (Fig. 1), and to present a revised model for the coastal evolution of these barriers.

GEOMORPHOLOGY OF THE GIPPSLAND LAKES

The Gippsland Lakes occupy an embayment penetrated by successive marine transgressions during the Pleistocene (Geological Survey of Victoria, 1977; Bird, 1978). Their landward extension is marked by a marginal bluff commonly about 20 m in height, but rising to 65 or 70 m in the east (Fig. 1). Seaward of the marginal

Fig. 2. Section at Tambo Bluff leading into Lake King. The bottom unit consists of massive, parallel bedded sand with minor iron nodule formation. It yielded a TL age $>79.6 \pm 9.6$ ka (Site 1: W1440). This unit has been interpreted as a marine sand extending below a lake level that lies within 1 m of present mean sea level. The marine unit is overlain by a chaotically sorted mass of muddy, gravelly sands that coarsen upward, and contains large blocks of iron-cemented sand. This upper unit forms a raised terrace that presently is gullied. It has been interpreted as a rapidly deposited fluvial sequence.

bluff, shallow coastal lagoons (Lakes Wellington, Victoria, and King) are separated from the ocean by a series of narrow, parallel, coastal barriers rising to average elevations of 4 to 8 m above present mean sea level. These sand bodies are 8 to 20 m thick and overlie a planed shelf of Pliocene or early Pleistocene bedrock. Six main river systems (Tambo, Nicholson, Mitchell, Perry, Avon, and Latrobe) drain into the lakes and are incised into a coastal plain that has undergone regional uplift throughout the Late Pleistocene. These rivers have supplied abundant sand for the development of extensive coastal barriers. They have also deposited terraces that in places, such as Tambo Bluff, cover marine deposits (Fig. 2). However, not all fluvial terraces (e.g., those in the Bark Hill region) can be linked to these river systems. Jenkin (1968) believed that the uplift in the region was spatially variable; however, Ward (1977) showed on the basis of uniform elevation of the terraces that differential earth movements had not occurred in the area.

Bird (1978) proposed an evolutionary model for the Gippsland Lakes, in which three main phases of barrier accretion occurred seaward of the marginal bluff (Fig. 3A). First, a "Prior" barrier of unspecified Late Pleistocene age formed at the landward side of the embayment between the Avon River in the west and the Mitchell River in the east. This barrier exists now as subdued recurved beach ridges spaced 100 to 150 m apart with swales about 2 m above mean lake level. Ward (1977) believed, on the basis of the degree of soil development, that deposits elevated

Fig. 3. Evolutionary models of Late Pleistocene barrier development in the Gippsland Lakes region: (A) according to Bird (1978), (B) according to Ward (1977).

around 3.4 m above mean sea level on Bird's Prior barrier were indicative of barrier deposition 42.5 ka ago (Fig. 3B). This age was based on correlation with deposits in South Carolina and New Zealand where higher Late Pleistocene sea level stillstands have been inferred stratigraphically (Ward et al., 1971). Ward also mapped higher level sand ridges and terrace deposits landward of the Prior barrier to elevations of 8 m. He believed these to be 63.7 ka in age.

The Prior barrier was overlapped seaward by a series of complex barriers forming the Inner barrier (Bird, 1978). Recurved and sequential beach ridge patterns indicate that this barrier grew from the west across the embayment toward Lakes Entrance at a sea level about 2 to 5 m above present lake level. The beach ridges, especially on Sperm Whale Head, appear subdued and have developed podsollic soils with a 1.0 to 1.5 m thick, white A2 horizon overlying illuvial orange-black humate. During the Last Glacial, strong westerly winds supposedly reworked the Inner barrier, producing large parabolic dunes that moved sand seaward to the east. These dunes are best developed at Pelican Point and Sperm Whale Head. Swamps in the arms of the dunes extend 6 m below present sea level, indicating formation of the dunes at lower sea levels. Controversy exists in the Boole Poole Peninsula region as to the age and extent of beach ridge formation. Bird believed that the ridges represented onlapping of Holocene beach sediments onto the Inner barrier, whereas Ward (1977) thought that all deposits in this region were 42.5 ka in age.

Finally, the Outer barrier was emplaced in its present position as a narrow, transgressive deposit parallel to refracted swell at the termination of the Holocene marine transgression 6,000 years ago (Thom, 1984). This progradation terminated about 3,000 years ago, with the shoreline remaining stable since then. This inferred chronostratigraphy can be traced throughout the region as far west as Corner Inlet (Fig. 1). However, except for the Holocene Outer barrier, no dating has been performed to confirm any aspects of the above models. It is the intention of this paper to fill in this gap in chronology.

THERMOLUMINESCENCE DATING PROCEDURES

The dating of coastal sediments using thermoluminescence (TL) is based on the measurement of TL energy acquired by crystalline minerals since their burial within a sedimentary unit. Therefore, the method requires that during transport, prior to burial, most of the previously accumulated TL energy is removed by exposure to solar ultra-violet radiation. Following deposition, TL energy once again builds up at a rate dependent on the radiation flux delivered by the long-lived isotopes of uranium, thorium, and potassium found in most sediment, with the fluxes from rubidium and cosmic radiation playing a lesser role. The length of time since the last exposure to sunlight thus is measured by determining the total amount of TL energy absorbed since deposition, or paleodose, relative to the rate at which this energy was acquired, or the annual dose. The technique used here is the combined regenerative/additive method applied to the 90 to 125 micron quartz fraction over a temperature range of 300° to 500°C (Duller, 1996). Summaries of the analyses are reported in Table 1.

TL always has been viewed as subject to a number of errors caused by (1) incompleteness of bleaching prior to deposition, (2) variations in long-term water content, (3) possible fluctuations in dose rates caused by weathering, and (4) differential leaching of uranium and thorium (Huntley, 1985; Readhead, 1988; Nott and Price, 1991). Because most of the Gippsland Lakes samples were collected in freely draining quartz sands, variable water content and weathering effects were judged as having an insignificant effect on the resulting TL ages. Partial bleaching generally results in ages that are too old. Such sediments rarely evidence a plateau over the complete 300° to 500°C temperature range on equivalent dose versus temperature plots. Thus, the wider the plateau, the less likely the problem of incomplete bleaching. Only 3 of the 23 analyses in the present study fail this plateau test (Table 1). Rather than being too old, these and other samples are too young if the commonly perceived models of Quaternary coastal evolution for Australia are applied to this coast. Leaching of uranium results in a decreasing annual dose rate over time. When this is related to the paleodose, it yields an older age. This problem does not appear to be evident in this study because many dates are younger than expected. Recently, the accuracy of TL has been assessed favorably in Australia against other dating techniques such as ^{14}C and uranium/thorium over a timespan of at least 65 ka (Gardner et al., 1987; Readhead, 1988; Nanson et al., 1991). TL also has been successfully correlated to similar, stratigraphically determined interglacial barrier chronologies over the past 800 ka (Huntley et al., 1993). All TL dates reported in

Table 1. Sample Numbers, Location and Ages of all Marine Deposits Dated using Thermoluminescence in the Gippsland Lakes Region of Victoria

Site no. ^a	Lab no. ^b	Location	Environment of deposition	Approximate elevation above msl	Palaeodose (grays)	K ^c (%)	Th and U chains (Bq/kg)	Annual dose ^d (μgrays)	Temperature plateau (°C)	TL age x ka ^e	Standard deviation x ka
1	W1440*	Tambo Bluff	Near shore	4 m	Middle Pleistocene >281.0 ± 33.0	1.60	88.9 ± 2.7	3,527 ± 61	300–500	>79.6	9.6
2	W1442	Waratah Bay	Barrier spit	33 m	183.0 ± 43.0	0.14	15.8 ± 0.5	584 ± 47	300–450	314	78.0
3	W1472*	Lake Tyers	Intertidal	40 m	>338.0 ± 36.0	0.95	64.1 ± 4.0	2,400 ± 74	300–500	>141	15.0
4	W1553*	Jemmys Point	Marine	12 m	>296.0 ± 32.0	1.85	70.8 ± 2.1	3,375 ± 55	300–500	>88.0	10.0
5	W1258	Beacon Pt.	Dune ridge	18 m	Last Interglacial 116.0 ± 11.0	0.39	36.8 ± 4.0	1,215 ± 70	275–500	95.7	10.7
6	W1555	Sandy Point	Barrier	15 m	39.7 ± 3.8	0.04	14.4 ± 0.5	469 ± 48	300–450	84.6	11.9
Phase One barriers (59–72 ka)											
7	W1434	Pelican Pt.	Dune	7 m	68.4 ± 6.6	0.47	20.2 ± 0.6	1,047 ± 50	275–500	65.4	7.0
8	W1435	White Cliffs	Dune	8 m	70.4 ± 5.4	0.50	24.7 ± 0.8	1,183 ± 51	300–500	59.5	5.2
9	W1438	Wattle Point	Beach	8 m	112.0 ± 14.0	0.37	52.7 ± 1.5	1,561 ± 52	275–475	71.6	9.0
10	W1439	Lakes Entrance	Beech ridge	4 m	74.7 ± 5.5	0.45	48.3 ± 1.3	1,327 ± 44	275–500	56.3	4.5
11	W1552	Banksia Peninsula	Barrier	4 m	96.4 ± 11.6	0.63	29.8 ± 0.9	1,393 ± 50	275–500	69.2	8.7
12	W1649	Longford	Barrier	15 m	142.4 ± 3.4	0.02	22.4 ± 0.7	608 ± 48	325–500	69.6	7.8
Phase Two barriers (40–48 ka)											
13	W1433	Collier Hill	Beach ridge	3 m	30.6 ± 4.5	0.09	21.6 ± 0.7	642 ± 48	275–500	47.6	7.8
14	W1551	Wattle Pt. Road	Beach	18 m	34.6 ± 3.4	0.09	24.0 ± 0.7	726 ± 50	275–500	47.6	5.7
15	W1554	Port Albert	Barrier	3 m	39.6 ± 2.6	0.63	19.3 ± 0.6	989 ± 41	275–500	40.0	3.1
16	W1650	Dowds Morass	Barrier ridge	7 m	41.8 ± 4.6	0.09	33.7 ± 1.0	879 ± 49	275–500	47.5	5.9
17	W1655	Yanakee	Barrier	20 m	28.2 ± 3.7	0.08	22.4 ± 0.7	678 ± 50	300–500	41.7	6.2
Phase Three (18–37 ka)											
18	W1257*	Lakes Entrance	Barrier	3 m	19.3 ± 0.7	0.83	8.0 ± 0.3	1,036 ± 43	275–425	18.6	1.0
19	W1259	Sperm Whale Head	Beech ridge	3 m	16.1 ± 1.8	0.09	15.4 ± 0.5	554 ± 49	275–500	29.0	4.2
20	W1436	Sperm Whale Head	Beachridge	3 m	20.0 ± 2.0	0.06	17.2 ± 0.5	547 ± 49	275–500	36.5	4.8
Holocene											
21	W1256*	Golden Beach	Back barrier	2 m	4.6 ± 0.7	1.45	12.4 ± 0.4	1,558 ± 40	300–400	30	0.4
Miscellaneous											
22	W1260	Bark Hill	Beach	8 m	18.1 ± 1.0	0.61	25.6 ± 4.0	1,262 ± 72	275–425	14.3	1.1
23	W1437	Bark Hill	Beach	4 m	216.0 ± 29.0	0.60	14.4 ± 0.4	1,084 ± 50	350–500	199	28.0

^aThe site number refers to the location of each sample in Figure 1.
^bRb levels are assumed to be 50 ppm unless indicated with an asterisk (*), where Rb levels are assumed to be 100 ppm.
^cK levels are determined by atomic absorption.
^dCosmic contribution to annual radiation dose is assumed to be 150 μgrays. Specific activity levels are measured by calibrated thick source alpha counting over a 42 mm scintillation screen assuming secular equilibrium.
^eAll TL determinations are carried out on 90 to 125 micron quartz sand fraction.

Fig. 4. Schematic cross-section of barrier stratigraphy and chronology in the central Gippsland Lakes area. The inferred stratigraphy and unit names are from Bird (1978). The number preceding each TL age refers to its site location in Figure 1.

this paper should be viewed as maximum ages because surface residual TL corrections have not been applied. Finally, it should be noted that the one standard deviation reported for the TL dates expresses the total experimental, environmental, and statistical uncertainty assigned to each parameter used in the analysis, and not just the statistical uncertainty of the measurement technique, as is usual in the reporting of ^{14}C ages.

CHRONOLOGICAL EVIDENCE FROM THERMOLUMINESCENCE DATING

Sites

The locations of 23 sites where TL was used to date sediments are shown on Figure 1. The choice of sites was selective, attempting to encompass all the divergent barrier features present along 200 km of coastline, as well as sampling deposits mapped by Bird (1978) and Ward (1977) within distinct, hypothesized chronological units. A schematic cross-section through the center of the Gippsland Lakes, encompassing a significant number of these TL dates, is presented in Figure 4. Generally, neither the degree of soil development nor juxtaposition of a feature in the landscape was indicative of its age, an aspect also found for coastal deposits along the New South Wales coast (Bryant et al., 1994). For instance, at Bark Hill west of Banksia Peninsula, two raised beaches mapped by Bird (1978) as part of the Prior barrier yielded widely disparate TL ages. Samples here were taken at a depth of more than 3 m from undifferentiated, well-sorted, coarse, orange sands. The lower of these beach units, lying 4 m above lake level, yielded a TL age of 199 ± 28 ka (Site 23: W1437), one of the oldest ages found in the Gippsland Lakes region. The upper adjacent beach unit, situated at an elevation of 8 m, gave a much younger TL age of 14.3 ± 1.1 ka (Site 22: W1260). Significantly, this latter sand showed evidence of incomplete bleaching. In contrast, ridges with well-developed podzols located seaward at Sperm Whale Head and Lakes Entrance yielded ages of 36.5 ± 4.8 ka (Site 20: W1436) and 56.3 ± 4.5 ka (Site 10: W1439), respectively. Overall, TL dating indicates the following chronology for coastal deposits in the region.

Evidence of Mid-Pleistocene Marine Deposition

The Gippsland Lakes region has been an area of marine deposition at least since the Middle Pleistocene. Whereas TL dating could not identify the precise age of these deposits, the presence of old marine sands is unequivocal. For example, marine sands from the marginal bluff were dated at Tambo Bluff (Fig. 2) and Jemmys Point. Both sites yielded saturated TL ages (Site 1: $>79.6 \pm 9.6$ ka, W1440, and Site 4: >88 ka, W1553, respectively). Iron nodules from Tambo Bluff also yielded a uranium/thorium age of 252^{+32}_{-43} ka (LH1966, Short, pers. comm., 1991). Additionally, marine intertidal sands containing oyster beds (*Neotrigonia* sp.) were sampled from a road cut west of Lake Tyers at an elevation of 40 m above present sea level. Both the TL age and a U/Th determination were inconclusive (Site 3: $>141 \pm 15$ ka, W1472, and >250 ka, LH1965, respectively). However, amino acid racemization performed on the oyster shells indicated a Middle Pleistocene age (Murray-Wallace, pers. comm., 1992). This latter age determination, if correct, is significant because the deposits are capped by the Haunted Hills Gravels, which have been interpreted as Pliocene in age (Geological Survey of Victoria, 1977). Finally, at Waratah Bay at the western boundary of the marine sequences, a raised barrier spit, situated at an elevation of 33 m above sea level, yielded a TL age of 314 ± 78 ka (Site 2: W1442), one of the oldest ages determined for a Quaternary marine deposit in Australia.

Last Interglacial Deposits

Last Interglacial deposits are absent in the Gippsland Lakes region—an unusual fact, given their pervasiveness along the adjacent New South Wales coast (Bryant et al., 1997). This aspect is shown in Figure 5, where TL ages are plotted for both regions as histograms over the period 12 to 300 ka. The global timing and duration of glacial and interglacial events, based on the $\delta^{18}\text{O}$ chronology of Martinson et al. (1987), is depicted for reference at the top of each panel. Note that the peak for the Last Glacial Maximum, based on U/Th mass spectrometry dating of corals, is shown at 22 ka (Bard et al., 1990). Only two deposits in the Gippsland region approximate a Last Interglacial age. One of these dates comes from a raised dune ridge from the Inner barrier at Beacon Point (Site 5: 95.7 ± 10.7 ka, W1258). This age, while not fitting the perceived 125 ka age for the Last Interglacial barrier building phase in Australia, corresponds with the age of a number of barrier deposits from oxygen isotope substage 5a/b found in New South Wales (Bryant et al., 1997). The second date was found in a subdued barrier feature at an elevation of 15 m above sea level at Sandy Point (Fig. 6). It yielded an age of 84.6 ± 11.9 ka (Site 6: W1555) and, although younger, overlaps with substage 5a.

Evidence for Interstadial Barrier Construction

TL dating techniques provide substantial evidence for Late Pleistocene interstadial barriers in the Gippsland Lakes region. The oldest of these deposits dates between 59 and 72 ka. Ages in this range come from two locations on the Prior

Fig. 5. Histograms of TL age determinations of Pleistocene marine coastal deposits: (A) sampled in the Gippsland Lakes region, 12 to 300 ka; (B) sampled along the New South Wales coast, 14 to 300 ka (Bryant et al., 1997). Glacial and interglacial stages as defined by the global paleo-temperature $\delta^{18}\text{O}$ curve (Martinson et al., 1987) have been added to the top of each panel.

Fig. 6. Raised barrier at Sandy Point lying 15 m above present mean sea level. The ocean is to the left. This feature is one of two deposits in the region possibly dating from the Last interglacial. It yielded an age of 84.6 ± 11.9 ka (Site 6: W1555), which overlaps with substage 5a. The barrier is backed by a younger marine deposit (Site 17: 41.7 ± 6.2 ka, W1655) lying 4 km further inland at an elevation of 20 m.

barrier: the first on a well-defined marine terrace up to 8 m above lake level at Wattle Point (Site 9: 71.6 ± 9.0 ka, W1438), and the second nearby on a raised beach ridge on Banksia Peninsula (Site 11: 69.2 ± 8.7 ka, W1552). Two eolian samples from high dunes within 4 km of each other at White Cliff and Pelican Point, on the back of the Inner barrier, also date within this interval (Site 8: 59.5 ± 5.2 ka, W1435, and Site 7: 65.4 ± 7.0 ka, W1434, respectively). In addition, a large marine deposit lying up to 15 m above sea level at Longford on the southern side of the Latrobe River also fits within this time span. This latter deposit consists of two well-sorted, coarse sand units 3 to 5 m thick with low dipping, parallel beds devoid of crossbedding. The lower unit yielded a TL age of 69.6 ± 17.8 ka (Site 12: W1649). Finally, humate from a beach ridge at Lakes Entrance may also belong to this interval (Site 10: 56.3 ± 4.5 ka, W1439).

A second phase of barrier accretion is evident between 40 and 48 ka. A beach ridge at Collier Hill (Site 13: W1433), lying several meters above the level of Lake Wellington, dates at this time. This ridge represents one of the earliest ridges formed by the eastward longshore transport of sediment on Bird's (1978) Inner barrier. The ridge has a relief of only 1.5 m and consists of organic-rich clayey sand in a well-developed podzol profile, with an impenetrable hardpan at 1.2 m depth. The sample was taken above the hardpan and yielded an age of 47.6 ± 7.8 ka. This date is replicated by sands from a raised terrace 18 to 20 m above sea level at the most shoreward part of the Prior barrier at Wattle Point (Fig. 7), and by sands in a ridge at Dowds Morass on the southeast corner of Lake Wellington. Their respective ages dated at 47.6 ± 5.7 ka (Site 14: W1551) and 47.5 ± 5.9 ka (Site 16: W1650). A raised barrier spit at an elevation of 20 m at Yanakie, shoreward of Waratah Bay in the westernmost part of the region, dated at a similar age (Site 17: 41.7 ± 6.2 ka, W1655). The Inner barrier at Port Albert, near Corner Inlet, also may have formed at this time (Site 15: 40.0 ± 3.1 ka, W1554).

Fig. 7. Marine sand deposited as a terrace 18 to 20 m above present sea level in front of the marginal bluff on the Wattle Point Road. The unit consists of clean, well-sorted sand forming a single massive bed about 3 m thick. It yielded a TL age of 47.6 ± 5.7 ka (Site 14: W1551). The unit overlies finer, parallel bedded sand to the right. The stratigraphic position of the deposit is shown in Figure 4. Note that an older marine unit (Site 9: 71.6 ± 9.0 ka, W1438) lies at a lower elevation seaward of this deposit.

A third phase of pre-Holocene barrier construction appears to be responsible for the geomorphic and soil differences noted by many researchers in the Boole Poole region. Sands from a low beach ridge on the seaward margin of Sperm Whale Head, and from a ridge at Lakes Entrance, yielded TL ages younger than 40 ka. The dates at Sperm Whale Head from the A2 and B horizons overlap in age (Site 19: 29.0 ± 4.2 ka, W1259, and Site 20: 36.5 ± 4.8 ka, W1436, respectively). The age of a ridge at Lakes Entrance is even younger (Site 18: 18.6 ± 1.0 ka, W1257). With the exception of three facts, it could be argued that these dates come from eolian sediments reworked towards the peak of the Last Glacial. First, samples come from distinct beach ridges that have lateral continuity, and in the case of Sperm Whale Head, form unmistakable parallel sets. Second, reworking would need to be responsible for the complete ridge form, because all samples were taken at a depth of 1.0 to 1.5 m, which approximates the relief of the ridges. Third, the Lakes Entrance sample was taken from a low ridge on the backbarrier flat on the Inner barrier, 50 m from a lagoon in a relatively protected position. The sand sample is overlain by 60 cm of stiff black clay coarsening upward into sand.

Holocene

A Holocene age for the Outer barrier was corroborated with a TL date taken at Golden Beach. Here, sand deposited on the backbarrier flat 2 m above mean sea

level was sampled at a depth of 0.5 m below a humic surface layer. It yielded an age of 3.0 ± 0.4 ka (Site 21: W1256). This young age provides confidence that marine sediments in the region can be bleached of any residual TL signature under normal wave processes. Thus, the ages presented above should be representative of the age of sediment within a few thousand years.

DISCUSSION

Significant fluvial and marine deposits dating since the Middle Pleistocene can be identified in the Gippsland Lakes region at elevations up to 40 m above present sea level. While the exact age of the oldest deposits remains to be determined, TL results indicate a complex process of sequential deposition and onlapping of marine and eolian sediments over the Late Pleistocene. The dating supports Ward's (1977) chronology and Bird's (1978) basic mapping of a sequential model of evolution. Last Interglacial barrier sediments appear to have been expunged mostly from the Gippsland Lakes embayment, with remnant sediments existing only at Beacon and Sandy Points (Fig. 1). In the latter case, sea level was at least 15 m higher than at present. Three phases of Late Pleistocene marine deposits are preserved in the region. The first phase dates between 59 and 72 ka, corresponding with Ward's 63.7 ka terrace level at 8 m and overlapping with Bird's Prior barrier deposits. However, this phase not only includes coastal deposits that are younger than those mapped by Ward, but also includes deposits extending to higher elevations. Barrier construction was restricted landward during this phase by the marginal bluff. These marine deposits have been eroded severely, such that now only isolated remnants are preserved. Deposits extend through a range of altitudes from 15 m at Longford in the west to present sea level at Lakes Entrance in the east. This trend supports either unequal recent uplift in the Gippsland Lakes region, a fact disputed by Ward (1977), or marine deposition over a range of sea levels near the coast. The second phase of barrier construction dates between 40 and 48 ka, and was separated from the first phase by an interval of widespread erosion. This phase corresponds to Ward's 42.5 ka deposits on the basis of soil development of both Prior and Inner barrier deposits. Ward mapped his deposits within 4 m of present sea level; however, TL-dated deposits from this second phase occupy a range of elevations from a maximum of 18 to 20 m, as evidenced by the terrace deposit at Wattle Point (Fig. 7) and the spit barrier at Yanakie (Fig. 1), to present sea levels, as evidenced by the recurved beach ridges at Dowds Morass and Collier Hill. Phase two deposition ended with a period of fluvial erosion. The third phase of barrier reorganization, corresponding to the Last Glacial, is problematic. Intriguingly, the evidence for this phase comes from the area between Sperm Whale Head and Lakes Entrance, where there has been considerable dispute as to the age of the barriers. This phase is characterized by the presence of subdued beach ridges. This last phase was truncated by Late Holocene deposition of the Outer barrier along the coastline.

The chronology presented above is unusual for two reasons. First, most of the marine deposits in the Gippsland Lakes embayment date at a time when sea levels globally were much lower than at present. The earlier two phases of sedimentation center on interstadial peaks around 40 to 50 ka and 58 to 68 ka (Martinson et al.,

1987), when sea level was relatively high but still eustatically 30 to 40 m lower than at present (Chappell, 1983). The difference in elevation can be explained only partially by tectonic uplift. Bryant (1992) showed, from a statistical analysis of sea level elevations around Australia during the the Last Interglacial, that the Gippsland Lakes region was characterized by plate upwarping ranging from 8 to 24 mm per thousand years. The present dating results support more rapid uplift. For example, the Waratah Bay date of 314 ± 78 ka at an elevation of 33 m (Site 2: W1442) suggests that the western part of the region has undergone uplift at a rate of 84 to 140 mm per thousand years. The elevations of raised barriers at Longford (Site 12: 69.6 ± 7.8 ka, 15 m) and Wattle Point (Site 14: 47.6 ± 15.7 ka, 8 to 10 m) suggest even higher rates of uplift of 168 to 215 mm per thousand years during the Late Pleistocene. These latter rates of uplift are some of the highest measured in Australia. For example, they surpass rates of 120 to 140 mm per thousand years measured in the eastern Coorong of South Australia, where Quaternary volcanism has been active, and overlap with the long-term average of 220 mm per thousand years measured across Bass Strait in northeast Tasmania (Bowden and Colhoun, 1984). In a global context, uplift in the Gippsland region can be regarded as slow to moderate (Bowden and Colhoun, 1984). When these rates are extrapolated over the last 40,000 to 70,000 years, they account for only 6.7 to 15.5 m of the 30 to 40 m required to place interstadial marine sands above present sea level.

The age of the third phase of deposition offers an alternative explanation. Its timing close to the Last Glacial Maximum, when sea level was up to 130 m below present levels, is similar to anomalously aged deposits mapped on top of Holocene sediment along the tectonically stable New South Wales coastline (Young et al., 1996; Bryant et al., 1997). The origin of the New South Wales deposits has been attributed to coastal overwashing by tsunami with deposition of relict shelf deposits during the Late Holocene. Here, tsunami have played a major role in coastal evolution throughout the Holocene (Bryant et al., 1996). It is possible that the same mechanism has operated in the Gippsland Lakes region at two scales: first, during interstadials, and second, during the Holocene. In the former case, marine sands close to an interstadial shoreline, at a lower sea level than at present, were swept to a considerable height inland without any apparent bleaching of their TL signature. In the second case, sands bleached of their TL signature during the Last Glacial, and bypassed by the Holocene marine transgression, were recently swept onshore from the present continental shelf. The age of the present Holocene barrier suggests that the age of this latter event preceded 3.0 ka. Although the TL age of the sands is correct, the anomalous location of such deposits alludes to subsequent transport and emplacement by a process, such as tsunami, that not only was rapid enough not to allow the TL signature to be bleached from the sands, but also catastrophic enough to deposit large bodies of sand inland. Thus, not all deposits may be indicative of rapid tectonic uplift. Tsunami overwashing also explains other features in the region: for instance, the presence of a sand layer beneath lagoonal clay at Lakes Entrance; the smoothed appearance of the Sandy Point barrier near Wilsons Promontory (Fig. 6); and the variably aged, raised beach deposits at Bark Hill. The stratigraphy at Lakes Entrance is similar to that produced by tsunami in estuarine environments in Scotland and Washington State (Long et al., 1989; Atwater and

Moore, 1992). Extensive fluvial erosion or backwash from tsunami events also may be responsible for the erosion of Last Interglacial deposits in the Gippsland Lakes region.

The source of the tsunami is probably the same as that responsible for shaping the New South Wales South Coast. Recently, we have focused on the Macquarie Ridge, at the edge of the Australian plate southwest of New Zealand, as the prime source for earthquakes that might generate tsunami approaching this corner of the continent. Such a source is all the more likely for the Gippsland Lakes region, given its closer proximity and the narrowness of the continental shelf leading into the Tasman Sea from Bass Strait (Fig. 1). The magnitude of the effects along the New South Wales coast now appears greater than that which an earthquake-generated tsunami could produce. Underwater sediment slides or comet impacts in the ocean are alternative mechanisms capable of generating the superwaves required to transport the amounts of anomalously aged sediment deposited inland in the Gippsland Lakes region. The occurrence of these types of events is yet to be proven. However, the steep bathymetry leading from the Tasman Sea into the Gippsland Lakes may be a possible source for slides, whereas the theoretical recurrence interval of an extra-terrestrial object, 200 m in size, in the Pacific Ocean is 24,000 to 43,000 years (Huggett, 1989). In the latter case, the resulting tsunami wave in mid-ocean could be 10 to 100 m high.

CONCLUSIONS

Without the use of modern dating techniques, the chronology of Late Pleistocene barrier complexes remains speculative. Nowhere is this more evident than in the Gippsland Lakes region of Australia, where various chronologies have been hypothesized based on stratigraphical or pedological evidence. Thermoluminescence dating provides a more precise chronology; however, in the case of the Gippsland Lakes, it raises problems as to the evolution of this barrier system. Whereas stratigraphical or pedological interpretations imply the development of parallel sequential barriers during interglacials on a coastline that is slowly undergoing uplift, TL dating suggests barrier formation on a rapidly rising coast during interstadials since 80 ka. Rates of tectonic uplift do not support this latter hypothesis without invoking the additional process of tsunami overwashing of the coast, a mechanism that has been substantiated along the nearby New South Wales coastline.

The sequence of Late Pleistocene marine deposits in the Gippsland Lakes region is so far unique for the continent. For example, in the Coorong region of South Australia where uplift has been similar, significant barriers have developed mainly during interglacial sea level stillstands without the apparent effect of catastrophic erosional events (Sprigg, 1952; Huntley et al., 1993). In New South Wales, where tsunami have been linked to barrier formation, interstadial coastal sediments have not been preserved in nearly as coherent a fashion as in the Gippsland Lakes region. The uniqueness of barrier formation in the Gippsland Lakes region, mainly during interstadials, can be attributed to the interaction of shoreward movement of abundant sediment, significantly rapid uplift, and the effect of tsunami within the confines of a shallow embayment. Further dating of deposits in this region, using

either TL or optically stimulated luminescence (OSL), should be performed to confirm this model of coastal evolution.

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